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Attributing long-term sea-level rise to Paris Agreement emission pledges

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The main contributors to sea-level rise (oceans, glaciers, and ice sheets) respond to climate change on timescales ranging from decades to millennia. A focus on the 21st century thus fails to provide a complete picture of the consequences of anthropogenic greenhouse gas emissions on future sea-level rise and its long-term impacts. Here we identify the committed global mean sea-level rise until 2300 from historical emissions since 1750 and the currently pledged National Determined Contributions (NDC) under the Paris Agreement until 2030. Our results indicate that greenhouse gas emissions over this 280-y period result in about 1 m of committed global mean sea-level rise by 2300, with the NDC emissions from 2016 to 2030 corresponding to around 20 cm or 1/5 of that commitment. We also find that 26 cm (12 cm) of the projected sea-level-rise commitment in 2300 can be attributed to emissions from the top 5 emitting countries (China, United States of America, European Union, India, and Russia) over the 1991–2030 (2016–2030) period. Our findings demonstrate that global and individual country emissions over the first decades of the 21st century alone will cause substantial long-term sea-level rise.

sea-level rise | Paris Agreement | emission pledges

Future global mean sea-level rise (GMSLR) poses a threat to ecosystems (1), the livelihoods of hundreds of millions of people (2), and world heritage (3, 4) along the Earth's coasts. Global mean sea level has risen by around 20 cm since 1900, with accelerating current rates of around 3 mm/y (5–7). The key contributors to sea-level change are ocean thermal expansion, glaciers, and the Greenland and Antarctic ice sheets, all of which are now contributing to current sea-level rise at an increasing rate in response to ongoing global warming (5). These contributors respond to warming on multiple timescales, ranging from decades to centuries for glaciers and centuries to millennia for thermal expansion and ice sheets (8, 9). Due to this long integrated response time, the GMSLR from anthropogenic greenhouse gas emissions is now only in its initial stages. A focus on the scenario dependency of GMSLR for the 21st century thus does not reflect the sensitivity of future long-term GMSLR to historical and future emissions as the full response to these emissions will only materialize on a millennial timescale (9–12).

For the near-term future up to 2030, aggregated Nationally Determined Contributions (NDCs), as submitted under the Paris Agreement framework, reflect the global mitigation ambition and result in quantifiable emission trajectories. The level of ambition implied by the NDCs is routinely compared to 2030 emission scenarios in line with 1.5 or 2 °C scenarios (13). Alternatively, the aggregated NDCs are translated into a Global Mean Temperature (GMT) signal up to 2100 for benchmarking against the Long-term Temperature Goal of the Paris Agreement (14). In contrast, the aspect of locked-in post-2100 consequences of near-term emissions has not been a central part of high-level political discourse. In this study, we use GMSLR modeling that can handle emission scenarios flexibly (15, 16) to establish the link between pledged NDC emissions and GMSLR until 2300, thus highlighting the longer-term climate change implications of current climate mitigation

efforts. We simulate the GMSLR commitment of greenhouse gas (GHG) emissions over the historical period (from 1750) and up to 2030, globally and for the 5 highest-emitting countries individually.

Attributing Global Mean Sea-Level Change to NDC Emission Pledges

We use a sea-level emulator (15) that includes contributions from thermal expansion, global glaciers, the Greenland Ice Sheet (GIS), the Antarctic Ice Sheet (AIS), and land-water storage. The emulator is part of the MAGICC simple climate model (17). Each component is calibrated to process-based projections consistent with the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5) (5) using a maximum likelihood optimization technique. In addition to the IPCC AR5 consistent AIS representation that captures surface mass balance effects (18) as well as solid ice discharge contributions with fast dynamics (19), we also implement an alternative version for AIS loss (20) that captures the higher sensitivity to future global warming from additional nonlinear processes related to Marine Ice Cliff Instability (MICI) (21). We use the MICI version to identify the potential for risk from higher sea-level rise not covered by our main results, but emphasize that the understanding of MICI and its triggers is still limited (22). Our sea-level emulator allows us to project GMSLR for emission scenarios until 2300. No estimates are provided

Significance

Sea-level rise poses a threat to coastal areas and will continue for centuries, even after global mean temperature has stabilized. Research assessing the implications of current international climate mitigation efforts usually focuses on 21st century climate impacts. The multicentennial sea-level rise commitment of pledged near-term emission reduction efforts under the Paris Agreement has not been quantified yet. We here estimate this sea-level rise commitment and find that pledged emissions until 2030 lock in 1-m sea-level rise in the year 2300. Our analysis highlights the defining role of present-day emissions for future sea-level rise and points to the potential of reducing the long-term sea-level-rise commitment by more ambitious national emission reduction targets.

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The authors declare no competing interest.

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Data deposition: Pathway as well as projection data and code to reproduce the results shown in this study can be accessed at: https://gitlab.com/anauels/ndc_slr_attribution.

See Commentary on page 23373.

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beyond this time horizon, as some information from process-based models used for the calibration (i.e., Antarctic solid ice discharge) is not available beyond 2300 (15).

Current NDCs are provided until the year 2030. With respect to GMT rise, the recent IPCC Special Report on Global Warming of 1.5 °C concluded that “pathways reflecting these ambitions would not limit global warming to 1.5 °C” (23). More specific projections regarding the long-term GMT implications of the NDCs are strongly dependent on assumptions about emissions after 2030. Assessments of the end-of-century temperature implications of NDCs commonly assume some form of continuation in ambition reflected in pledged climate mitigation targets (24).

Here we follow a different approach that aims to avoid uncertainties regarding future ambition levels by analyzing stylized emission scenarios with zero Kyoto-GHG emissions after the end of the NDC accounting period in 2030. Assuming abrupt zero aerosol emissions would lead to a short-term increase in GMT (Fig. 1B). In order to avoid artifacts of such abrupt warming on long-term sea-level rise (Fig. 1C), we decrease aerosols and all other gases not regulated under the Kyoto protocol until 2075 (*Methods*). This stylized approach allows us to isolate the effects of NDCs and country-level emissions on longer-term GMSLR without making assumptions about global or individual country emissions pathways after 2030.

Cumulative NDC CO₂ emissions relative to preindustrial are estimated to reach around 765 gigatonnes of carbon (GtC) in 2030. Fig. 1 depicts total anthropogenic CO₂ emission estimates (A) and resulting probabilistic 2100 GMT (B) and GMSLR (C) responses for our 2030 NDC pathway. For illustration purposes, we also provide estimates for a representative 2 °C warming comparison pathway (RCP2.6) and the NDC extension pathway by the Climate Action Tracker (CAT) consortium (24, 25). For the GMT response, we can identify the diminishing influence of short-term climate forcers in the first decades after the year of zero emissions.

The global 2030 NDC pathway allows us to quantify the NDC GMSLR commitment in 2100 and 2300, accounting for historical emissions since 1750. The chosen time frame up to 2030 further allows us to assess the contribution of individual emitters. To isolate country-level emission shares, we define 2 emission accounting periods for which country-level information is available (*Methods*). We call the first period from 1991 to 2030 the “IPCC period” as the first IPCC report was published in 1990. The second period from 2016 to 2030 is termed the “Paris period” as it exclusively covers the emissions after the 2015 Paris Agreement

until 2030 (pre-2020 commitments and NDCs). For both accounting periods, emissions of the 5 biggest emitters (China, United States of America [USA], European Union [EU28], India, and Russia) are individually removed from the reference 2030 NDC pathway (Fig. 2). We estimate that China is responsible for 83 (44) GtC, the USA for 59 (21) GtC, the EU28 for 41 (13) GtC, India for 19 (11) GtC, and Russia for 18 (7) GtC of CO₂ emissions over the IPCC (Paris) periods (25, 26).

For our global NDC pathway, we project a median peak warming of around 1.5 °C (66% range: 1.3 to 1.7 °C) relative to 1750 for the year 2035, then declining to a committed warming of around 1.3 °C (1.0 to 1.7 °C) in 2100 (Fig. 1B). For the top 5 emitters combined, historical and pledged emissions until the end of the first NDC period cause a 2100 warming of 0.45 and 0.2 °C for the IPCC and Paris periods, respectively (Fig. 2B and E).

National-Level GMSLR Commitments

In response to the warming trajectories of historical emissions, pledged NDC emission reductions, and zero GHG emissions after 2030, we estimate that, relative to the IPCC AR5 reference period 1986–2005, GMSLR will rise by 43 cm (66% range: 34 to 54 cm) in 2100 and continue to increase by 105 cm (79 to 135 cm) in 2300 (Fig. 2 and Table 1). The 2300 GMSLR commitments of global emissions prior to the IPCC (1991) and Paris (2016) periods yield around 60 (48 to 75) cm and 84 (66 to 109) cm, respectively. Using the IPCC accounting period (1991–2030), pathways that exclude 1 of the top 5 emitters reduce median 2300 GMSLR by around 10 cm for China, 7 cm for the USA, 5 cm for the EU28, and 2 cm for India and Russia (Table 2). For this 40-y period, the top 5 emitters are therefore responsible for a median of around 26 cm GMSLR in 2300, which is more than the roughly 20 cm observed since the beginning of the 20th century and about 25% of the total 2300 GMSLR NDC commitment. Using the Paris accounting period (2016–2030), the median 2300 GMSLR contribution ranges from roughly 6 cm for China, 3 cm for the USA, 2 cm for the EU28, and about 1 cm for India and Russia. For the 15-y Paris timeframe, the top 5 emitters thus commit GMSLR to a median of around 12 cm, more than 50% of the observed 20th century GMSLR.

For both accounting periods, country-level GMSLR contributions reflect changes in relative emission shares and therefore underline the overall sensitivity of 2300 GMSLR to changes in near-term emissions (Fig. 3). The fossil-fuel-intensive histories of the USA and EU28, for example, move both their CO₂ emission

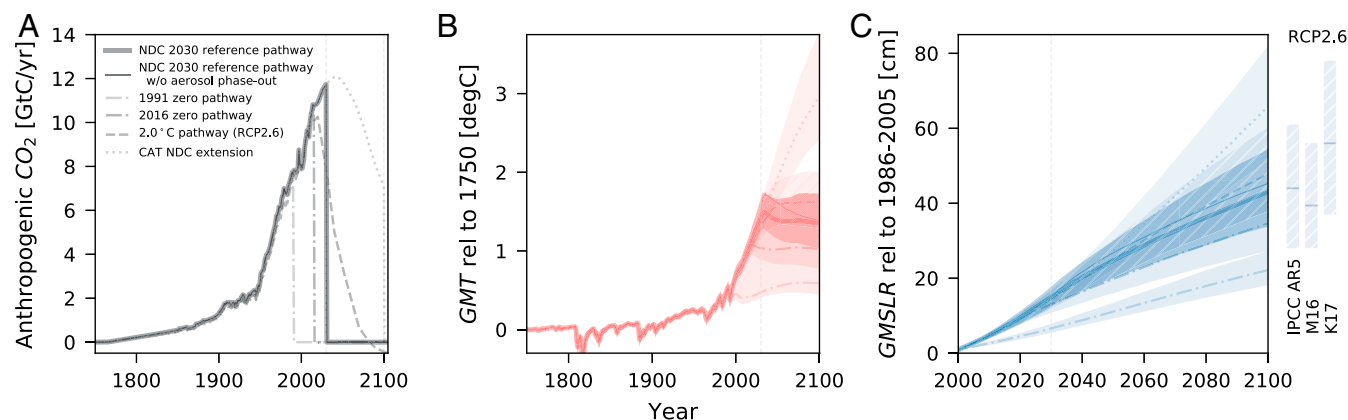


Fig. 1. Total annual CO₂ emissions including land use (GtC/y) (A), resulting median GM (B), and GMSLR (C) projections for the stylized zero 2030 NDC reference pathway (solid), zero 1991 and 2016 pathways (dash-dotted), as well as 2 °C (dashed) and NDC extension comparison pathways (light dotted). In 1991, 2016, and 2030 zero pathways, all GHG are set to zero in respective years except for aerosols and non-Kyoto gases which are phased out exponentially until 2075 (*Methods*). The median GMT and GMSLR responses for the 2030 NDC reference pathway without aerosol phase-out are also shown (dotted). Projected 2100 GMSLR median and 66% ranges under RCP2.6 from IPCC AR5, M16 (16), and K17 (41) are shown for comparison. GMT is provided in °C relative to 1750, IPCC AR5-consistent GMSLR is provided in cm relative to the 1986–2005 average. Shaded GMT and GMSLR uncertainties reflect the 66% model ranges.

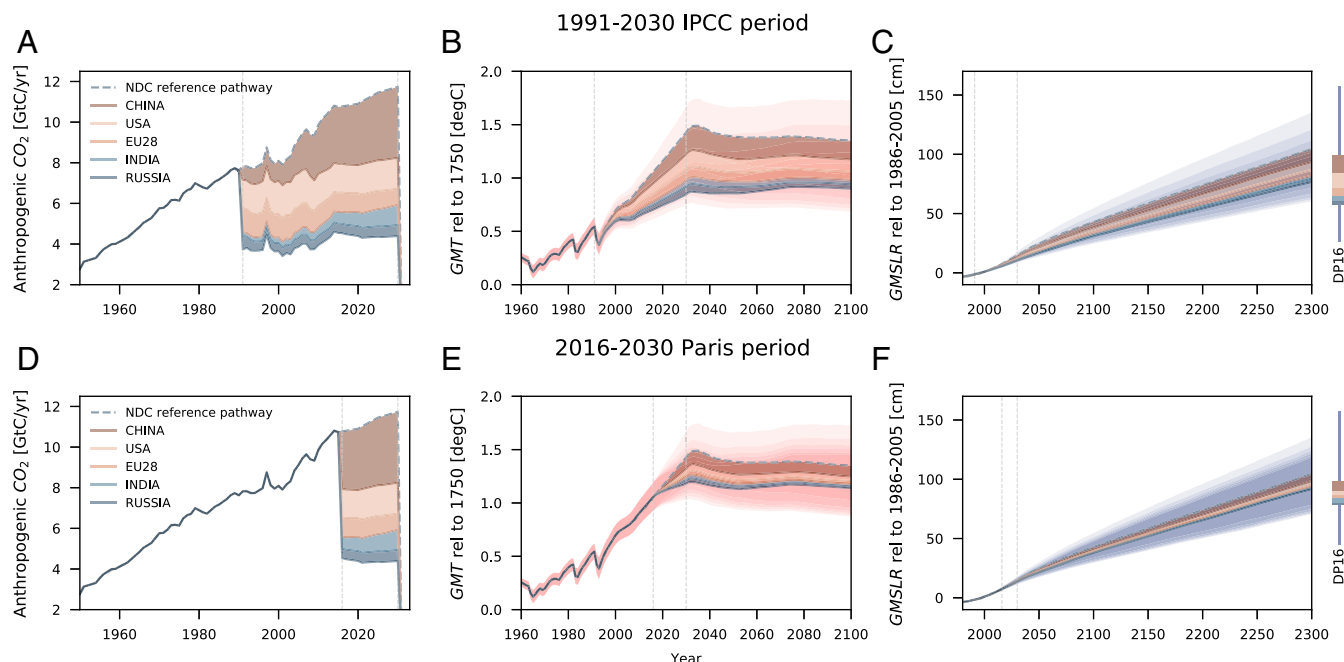


Fig. 2. Country-specific total CO₂ emission shares (GtC/yr) of the biggest 5 emitters (A and D) and resulting median 2100 GMT (B and E) and 2300 GMSLR (C and F) contributions for the IPCC (1991–2030) and Paris (2016–2030) emission accounting periods. GMT is provided in °C relative to 1750; IPCC AR5-consistent GMSLR is provided in centimeters relative to the 1986–2005 average. Shaded GMT and GMSLR uncertainties reflect the 66% model ranges. Bars on the right show median 2300 GMSLR projections, country shares, and overall 66% uncertainty range based on the alternative DeConto and Pollard (DP16) parameterization (19).

and resulting GMSLR shares closer to China for the IPCC period, while for the Paris period, the projected decrease in fossil-fuel intensity for the EU28 shifts the country group toward the growing CO₂ emissions and respective GMSLR contributions of the developing economy of India (Fig. 3). Unlike historical emissions until 1991 or 2016, pledged national emissions until 2030 are not yet locked in, but if they are followed, they will cause ~20 cm of GMSLR in 2300. When focusing on the Paris period, the attributable country contributions to projected long-term GMSLR emphasize the impact of countries' emissions during both the IPCC and Paris periods and clearly point to the potential of reducing the future GMSLR commitment by more ambitious national emission reduction targets.

We also tested our results to the sensitivity of model choice for Antarctic ice discharge by including the MICI mechanism (20, 21), denoted DP16 in the following. Median sea-level estimates and uncertainties for 2300 are shown as vertical bars in Fig. 2. Based on this sensitivity test, the top 5 emitters would be responsible for around 41 cm GMSLR in 2300, using the IPCC accounting period (Fig. 2). For the Paris period, the top 5 emitters together would cause a GMSLR commitment of about 20 cm.

While the median GMSLR commitments resulting from the DP16 sensitivity test (20, 21) are lower than in our main results,

they also show a wider sea-level response range to carbon emissions. This reflects the fact that our MAGICC ensemble has a wider range of temperature responses than the temperature responses used in DP16, with rare strong warming triggering MICI-style ice loss, and that the emulated DP16 reference data contain individual ensemble members that do not show ice loss until 2300 under strong mitigation (20). We note, however, that the temperatures identified by DP16 for triggering MICI are anomalously low with respect to projections using a combination of satellite observations, an established polar regional climate model, and climate models from the Coupled Model Intercomparison Project 5 (27). This suggests that the temperature thresholds for triggering MICI in the sea-level emulator should be higher than used here, making it even less likely that MICI would be triggered by the warming associated with the global NDC pathway used in our study. Recent work has also pointed to other uncertainties associated with the MICI hypothesis, including the strength of the MICI feedback, how it might vary in different locations, and the possibility that it might be mitigated by associated responses (freshwater entering the ocean, buttressing by ice mélange, changes in relative sea level from gravitational and solid-Earth effects) (22). Given that the MICI hypothesis is based on only 1 study and is subject to a wide range of uncertainties, further work is required to assess the implications of this ice-sheet instability mechanism for our results.

Estimating the sea-level contributions for pledged emission reductions of individual countries relies on a set of assumptions and caveats. Our scenarios are simplified and stylized as Kyoto-GHG emissions are reduced to zero after 2030 to isolate the sensitivity of GMSLR to IPCC and Paris-period-only emissions. While a real-world energy system cannot produce such a step-change reduction, it is appropriate for our attribution design, which focuses mainly on identifying differences in sea-level responses. Emissions are not a state variable, but a flux. The flux step change can be handled by models like MAGICC, resulting in peak-and-decline temperature responses (28). Projected GMT changes have been the subject of several similar experimental designs (29, 30).

Table 1. GMSLR commitment in 2100 and 2300 for cumulative CO₂ emissions until 1991, 2016, and 2030

	CO ₂ emissions, GtC	2100 GMSLR, cm	2300 GMSLR, cm
Global			
1991	385	22.2 (18.2 to 27.3)	58.8 (47.7 to 74.6)
2016	608	34.6 (27.2 to 43.6)	84.2 (65.5 to 109.4)
2030	765	43.0 (33.8 to 54.4)	104.6 (78.5 to 135.4)

IPCC AR5-consistent GMSLR median projections and 66% ranges are provided relative to the 1986–2005 average. Estimates for anthropogenic CO₂ emissions including land use are calculated relative to 1750.

Table 2. GMSLR commitments in 2100 and 2300 for CO₂ emission shares of the 5 highest-emitting countries over the specific IPCC (1991–2030) and Paris (2016–2030) accounting periods

	CO ₂ emissions, GtC		2100 GMSLR, cm		2300 GMSLR, cm	
	1991–2030, IPCC period	2016–2030, Paris period	1991–2030, IPCC period	2016–2030, Paris period	1991–2030, IPCC period	2016–2030, Paris period
Top 5	220	95	12.3 (9.2 to 16.7)	5.3 (4.0 to 7.0)	26.2 (18.5 to 37.8)	11.8 (8.4 to 16.9)
China	83	44	4.6 (3.5 to 6.2)	2.4 (1.8 to 3.2)	10.0 (7.0 to 14.3)	5.5 (3.8 to 7.7)
USA	59	21	3.1 (2.4 to 4.3)	1.1 (0.8 to 1.5)	6.8 (4.8 to 9.8)	2.5 (1.8 to 3.6)
EU28	41	13	2.2 (1.6 to 3.0)	0.7 (0.5 to 0.9)	4.7 (3.3 to 6.8)	1.5 (1.1 to 2.2)
India	19	11	1.2 (0.9 to 1.6)	0.6 (0.5 to 0.8)	2.4 (1.7 to 3.5)	1.4 (1.0 to 2.0)
Russia	18	7	1.2 (0.9 to 1.7)	0.5 (0.4 to 0.7)	2.4 (1.7 to 3.5)	1.0 (0.7 to 1.4)

IPCC AR5-consistent GMSLR median projections and 66% ranges are provided relative to the 1986–2005 average. GMSLR contributions and estimates for anthropogenic CO₂ emissions including land use are calculated for the 5 highest-emitting countries individually and in an aggregated way (Top 5).

Our experiment of assuming no further emissions beyond 2030 provides a lower bound for future sea-level-rise impacts. Reaching net-zero GHG emissions from current NDC levels will take several decades (23), which indicates that the real risks implied by 2030 NDC levels will be substantially higher. Our main results exclude the higher sensitivity to global warming introduced by MICI and hydrofracturing processes, but our sensitivity tests indicate that, as currently understood, MICI can increase the contribution of the Antarctic ice sheet for stronger global warming. Finally, our approach does not cover the possibility of greater emissions by 2030 than currently pledged by the NDCs, which may lead to an underestimation of the presented sea-level commitments.

The assessment of future sea-level change needs to address the associated high uncertainties. While the future responses of thermal expansion and glaciers are reasonably well understood, the future responses of the ice sheets, in particular the AIS with its multimeter GMSLR potential, remain poorly constrained. The MICI hypothesis, which was proposed after IPCC AR5, leads to

higher estimates for the future AIS GMSLR contribution, especially under strong future global warming (21, 22). However, because MICI is still under debate (22) and new insights are expected from future work, we present sea-level-rise estimates including MICI only as a sensitivity test.

Furthermore, our applied methodology includes a parameterization for the sea-level contribution from land-water storage which is not dependent on climate change (15). This scenario-independent median land-water contribution of around 21 cm for 2300 is based on the extrapolation of the modeled end-of-21st-century response (31). The total NDC GMSLR commitment presented here encompasses this land-water estimate and is sensitive to its changes, highlighting the large uncertainties associated with absolute GMSLR projections. The derived relative GMSLR commitments for the top 5 emitters, however, would not change as they are not sensitive to the absolute land-water contribution but only determined by the climate-driven sea-level responses to the 2030 NDC reference pathway.

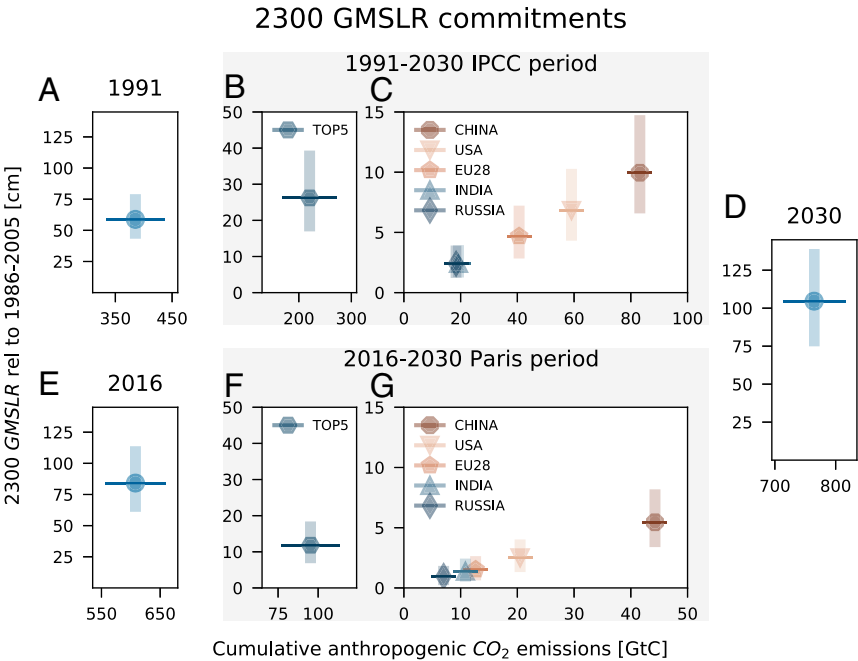


Fig. 3. GMSLR commitments and 66% uncertainty bars for the year 2300, as well as corresponding cumulative anthropogenic CO₂ emissions for the top 5 emitters, using the 1991–2030 IPCC (B and C) and 2016–2030 Paris emission accounting periods (F and G). In addition, 2300 GMSLR commitments for cumulative emissions until 1991 (A) and 2016 (E) are provided together with projected total 2030 GMSLR commitment (D) based on available 2030 NDC emission pledges. IPCC AR5-consistent GMSLR is provided in centimeters relative to the 1986–2005 average. Please note the different y-axis scaling for global GMSLR commitments provided in A, D, and E and the specific emission accounting periods in B, F, C, and G.

The 2300 Sea-Level Legacy of Near-Term Emissions

Sea levels will continue to rise long beyond 2300 (9, 12). Constrained by our methodological setup, however, 2300 emerges as a pragmatic focal point for the analysis of commitments as it allows us to assess GMSLR differences for near-term emission reduction trajectories. Our analysis demonstrates that even GHG emissions over the first decades of the 21st century will shape coastlines around the globe for centuries to come. Previous research conducted with different sea-level models and experimental setups reached similar conclusions (11, 12). By linking 2300 GMSLR with combined historical emissions and 2030 NDC emission reduction pledges on a country level, we provide an angle to assess the climate impact implications of near-term national emission reduction targets, extending the scope beyond, for example, NDC implications of extreme temperature (32).

Our findings also underscore the relevance of present-day emissions in shaping the multicentury sea-level-rise response. About 44% (20%) of the total 2300 GMSLR commitment for emission from preindustrial until 2030 can be attributed to emissions of the IPCC (Paris) period. GHG emissions by the top 5 emitting countries over the same periods contribute to 25% (12%) of the 2300 total. The 15 y from 2016 to 2030 commit about 8 cm of additional sea-level rise in 2100 or 20 cm of additional sea-level rise in 2300 (Table 1), with the latter estimate being roughly equivalent to what has occurred since the preindustrial period. Only stringent near-term emission reductions in line with achieving the 1.5 °C long-term temperature goal of the Paris Agreement would provide a chance of limiting long-term sea-level rise to below 1 m (11). Since the adoption of the Paris Agreement, however, global GHG emissions have not shown a sign of peaking (33), while the current NDCs are inadequate to put the global community on track to meet the Paris Agreement Long-term Temperature Goal by the end of the 21st century (14).

Attributing GMSLR to pledged emission reductions not only highlights the importance of strong near-term mitigation efforts, but also emphasizes the inevitability of future coastal adaptation as well as loss and damage needs related to committed multicentennial GMSLR. Our ability to quantify and attribute such global sea-level commitments raises highly policy-relevant questions with respect to the need and responsibilities of supporting adaptation and loss and damage responses in low-lying coastal zones and small islands that will experience the most severe impacts.

Methods

We use both observed and projected GHG emissions to generate the suite of 2030 pathways used in this study. Until 2014, MAGICC was used to derive emissions from the CMIP6 historical GHG concentrations (34–36). The 2015–2030 emissions consistent with Paris Agreement NDCs are taken from the CAT high-pledge scenario (25). The 2030 NDC pathway is extended until 2100 using the constant quantile extension described in Gütschow et al. (24). The translation of the obtained pathway into the individual GHG input for the simple climate carbon-cycle model MAGICC (17) is based on an updated Equal Quantile Walk (EQW) method described in Meinshausen et al. (37). The updated EQW method uses recent scenario databases (AR5, Shared Socioeconomic Pathways, and IPCC special report on 1.5 °C of global warming) but the same methodology as the original EQW which is based on older scenarios like the IPCC Special Report on Emissions Scenarios.

We harmonize the CAT emissions to historical emissions with a harmonization factor linearly fading out until 2030 such that we obtain a smooth transition from historical emissions to the CAT NDC emissions levels. After 2030, we set all Kyoto-GHG (CO₂, CH₄, N₂O, and fluorinated gases) to zero and fade out emissions from other substances (SO_x, NO_x, CO, OC, non-methane volatile organic compounds, BC, and NH₃) exponentially from 2030 until 2075 to avoid a rapid temperature increase after 2030 because of

the sudden removal of substances with short-term effects. The pathway obtained by this procedure is our NDC reference pathway.

In order to derive the country-emission shares of the top 5 emitters for the 2016–2030 period, the relative Kyoto-GHG contribution of the NDCs is normalized to the emissions of the year 2015. For each GHG input, the following temporary pathway is generated:

$$Et_{c,g}(y) = E_{c,g}(2015) \times G_{global,g}(y) \times G_c(y),$$

where $E_{c,g}(y)$ are the emissions of country c for gas g in year y ,

$$G_c(y) = E_{c,KyotoGHG}(y) / E_{c,KyotoGHG}(2015),$$

is the time series of the country relative to 2015, and

$$G_{global,g}(y) = (E_{global,g}(y) / E_{global,g}(2015)) / (E_{global,KyotoGHG}(y) / E_{global,KyotoGHG}(2015))$$

is the global time series for the gas g , relative to 2015 and relative to the aggregate Kyoto gas time series. This temporary pathway is scaled such that the sum for all gases matches the CAT scenario for the country for all years:

$$E_{c,g}(y) = Et_{c,g}(y) / \text{sum}_g(Et_{c,g}(y)) \times \text{CAT}_c(y).$$

Before 2016, we directly use the historical gas shares as available from the PRIMAP-hist dataset (26, 38). Two scenarios are created for each of the top 5 emitting countries, one where the country's emissions are removed starting in 1991 and one where they are only removed starting in 2016. We only remove Kyoto GHGs and phase out non-Kyoto gases as done for the 2030 reference pathway, as changes in historical emissions for other substances influence the internal calibration of MAGICC. To quantify the global GMSLR commitment until 1991 and 2016, zero Kyoto-gas pathways are designed starting for these years by applying a similar methodology to the 2030 reference pathway design. Here, non-Kyoto gases are phased out as early as possible for the 1991 pathway starting in 2006 (to not affect the internal MAGICC calibration), and for the 2016 zero pathway starting regularly in 2016. For all pathways, radiative forcing is held constant after 2100 until 2300.

We use the simple climate carbon-cycle model MAGICC version 6 (17) to translate generated GHG emission pathways into GMT responses. For every pathway, probabilistic GMT projections are generated with a historically constrained ensemble of 600 runs, derived by a Metropolis–Hastings Markov chain Monte Carlo approach (39). Model parameters of the ensemble are chosen to capture IPCC AR5 equilibrium climate sensitivity estimates (40, 41) and carbon-cycle uncertainties (42). As such, the probabilistic MAGICC modeling framework consistently covers model and climate-related uncertainties. The model is run for the period 1750–2300.

The MAGICC sea-level model (15) is one of several existing simplified approaches to project sea-level change (16, 43–45) and emulates IPCC AR5 process-based SLR projections (5) and provides GMSLR estimates for all major climate-driven sea-level components including thermal expansion, global glacier mass changes, the surface mass balance, and solid ice discharge components of the Greenland and Antarctic ice sheets, as well as the non-climate-driven land-water storage contribution. For each of the probabilistic 600 ensemble members, calibrated sea-level parameters are sourced randomly for every sea-level component. The Antarctic ice sheet solid ice discharge component was extended (20) to include a threshold-temperature parameterization to capture potentially higher Antarctic sensitivity through hydrofracturing and subsequent MICI that would substantially increase future SLR projections under high-emission scenarios (21). Since the MICI hypothesis is subject to ongoing scientific debate (22, 46), we only use these projections for a sensitivity test. The MAGICC sea-level model provides projections from 1850 to 2300, constrained by the availability of reference data, in particular for the Antarctic solid ice discharge response (19).

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